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Evaluation and comparison of current biopsy needle localization and tracking methods using 3D ultrasound

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ABSTRACT

This article compares four different biopsy needle localization algorithms in both 3D and 4D situations to evaluate their accuracy and execution time. The localization algorithms were: Principle component analysis (PCA), random Hough transform (RHT), parallel integral projection (PIP) and ROI-RK (ROI based RANSAC and Kalman filter). To enhance the contrast of the biopsy needle and background tissue, a line filtering pre-processing step was implemented. To make the PCA, RHT and PIP algorithms comparable with the ROI-RK method, a region of interest (ROI) strategy was added. Simulated and ex-vivo data were used to evaluate the performance of the different biopsy needle localization algorithms. The resolutions of the sectorial and cylindrical volumes were 0.3 mm × 0.4 mm × 0.6 mm and 0.1 mm × 0.1 mm × 0.2 mm (axial × lateral × azimuthal) respectively. In so far as the simulation and experimental results show, the ROI-RK method successfully located and tracked the biopsy needle in both 3D and 4D situations. The tip localization error was within 1.5 mm and the axis accuracy was within 1.6 mm. To the best of our knowledge, considering both localization accuracy and execution time, the ROI-RK was the most stable and time-saving method. Normally, accuracy comes at the expense of time. However, the ROI-RK method was able to locate the biopsy needle with high accuracy in real time, which makes it a promising method for clinical applications.

1. Introduction

The last two decades have seen a great improvement in diagnostic ultrasound technology. This has led to an expansion in the domains of application of the modality, such as ultrasound-guided interventions and therapies [1]. Such operation can be used in human liver, prostate, kidney and even heart. In order to reduce the risk of internal injuries to human tissue, increasing interest has been paid to improving ultrasound navigation systems and to automated localization algorithms for medical micro-tools.

Since human tissue has a 3D structure, using 3D ultrasound technology to scan the target region can elucidate the spatial structure of the tissue, in addition to providing 3D positioning information of micro-tools, especially biopsy needles inserted into tissue. Thus, more and more biopsy needle localization algorithms utilizing 3D ultrasound imaging have been developed. These localization algorithms are generally focused on four categories of mathematical theories: (a) eigen-decomposition methods such as principle component analysis (PCA) [2]; (b) transform based methods such as the Hough transform (HT) [3]; (c) projection methods such as a special form of Radon transform [4,5], and parallel integral projection (PIP) [6,7]; (d) iterative learning algorithms such as random sample consensus (RANSAC) [8,9]. However, in real-world applications these localization methods face several challenges:

(a) Calculation complexity: Due to the substantial calculation requirements of the algorithms and the large quantity of voxels in a single 3D ultrasound volume, calculation complexity is a great challenge for localization algorithms. The large quantity of calculation required can lead to a nonreal-time-lag in the localization results.
(b) Localization accuracy: Due to intrinsic characteristics of ultrasound image formation, there may be attenuation, speckle, shadows and other artifacts in the image. Together, these facts may make precise localization in 3D ultrasound a very challenging task.
(c) Localization stability: In clinical applications, needle insertion is a dynamic procedure. In this case 4D ultrasound is utilized, whereby 3D ultrasound volumes are continuously acquired and displayed in real time [10]. Thus, the biopsy

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needle localization method must precisely locate the needle in each 3D volume of the imaging series. Missing localization in any volume may cause the failure of the algorithm. Stability therefore, becomes another challenge for localization methods.

Much effort has been directed into countering these challenges. Some research groups have improved robotic-guided micro-tool localization systems for real-time clinical applications. For example, Krupa et al. first developed a robotic vision system which automatically located the position of surgical tools during robotized laparoscopic surgeries [11]. To stabilize the motion of soft tissue in-plane and out-of-plane, speckle tracking methods were developed and a visual servo control scheme was also applied [12]. Some research groups using the needle reflection pattern to facilitate the needle localization framework. Daoud et al. have proposed a new method to localize the biopsy needle in curvilinear ultrasound images. This method transmits a circular ultrasound wave and the received signals are analyzed to determine the arrival times of the needle echoes. The needle axis can be located using the echoes arrival times and the known needle reflection patterns [13]. Other groups use the external equipment to help the instrument tracking procedure. Stolka et al. proposed to use the stereo cameras, which, mounted on the ultrasound probe, can estimate the needle position and track the needle tip [14]. However, the external facilities introduce further difficulties, such as the design of automatic control algorithms of the robotic system, and the cost of such a system is relatively high. Thus, in this paper we concentrate on a conventional 3D ultrasound system and a human controlled biopsy needle insertion procedure. Moreover, the needles used in the work described here were conventional rigid metal ones without any echogenic enhancement as described in Nichols et al. [15].

A PCA algorithm method for biopsy needle localization was first proposed by Draper et al. [16] using 2D ultrasound. Novotny et al. updated this method to 3D ultrasound volumes [17]. Following on from PCA, the HT algorithm was also introduced into straight needle localization methods. Zhou et al. implemented two modifications of the classical HT for tool localization; the 3D HT algorithm and the 3D Randomized HT (3DRHT) [18]. The 3DRHT is less resource (memory and time) consuming than the 3DHT algorithm. Since the Radon transform has the potential to detect a line-segment in 3D data, it has been implemented in biopsy needle localization directly from the RF signal as well as in the reconstructed US image [5]. From this research work, Mari et al. [6] firstly proposed the PIP algorithm, which is actually a special form of Radon transform, demonstrating its use in the localization of a thin electrode inserted into a Cryo-Gel phantom. Later, Barva et al. improved this method increasing its automation and practicality [7].

Since the above methods can only locate straight needles, Uherčík et al. introduced the model-fitting (MF) RANSAC algorithm for biopsy needle localization [9]. Through changing the different line model, MF RANSAC was able to locate not only straight needles, but also C-like and S-like ones. Even though the methods above are claimed to be highly accurate, they still suffer the cost of a long calculation time. Localization in a dynamic situation was not discussed, neither. To design an algorithm more applicable to real situations, which is to say a localization and tracking situation, Zhao et al. [19] proposed a dynamic localization method named ROI-RK, which is developed from the previous MF-RANSAC algorithm proposed by Uherčík et al. [9]. In this method, a region of interest (ROI) strategy was implemented to limit the quantity of calculation, as well as inclusion of a Kalman filter to increase the stability of the tracking. To decrease the calculation time of some of the methods introduced previously [7,17,18], a ROI strategy was added to each localization method. Machine learning techniques have also been proposed in this domain. Ayvaci et al. [20] first proposed to segment the needle from the background by minimizing an energy function from MRI/TRUS fusion-guided biopsy videos. Uherčík et al. chose the intensity and tubularness of a voxel [21] to form a feature vector and then used different classifiers to segment the biopsy needle from 3D ultrasound volumes [22]. However, machine learning methods need a pre-trained model to assure segmentation performance, they cannot be directly compared with unsupervised needle localization methods. In the previous work [19], the performance of ROI-RK method has been evaluated using simulated 3D volumes. In this study, the different methods are compared based on some parameters from [19], for example the choice of threshold value, and the evaluations of their accuracies and robustness are all presented. Moreover, *ex-vivo* data have been used to evaluate the needle localization methods.

A comparison study of biopsy needle localization methods in 2D ultrasound has been performed by Zhao et al. [23]. When using 2D ultrasound, usually a needle guide is implemented to maintain the biopsy needle in the image plane, for example, in prostate therapy. However, in some case, the fixed needle guide could limit the inserting path of the needle. Since human tissue has 3D structure, 3D ultrasound has been proposed in the use of locating and tracking the biopsy needle in the minimally invasive therapy. From the larger field of view of 3D ultrasound image, the spatial position relationship of tissues, vessels and biopsy needle can be observed. It has superiority for some human organs, such as in liver biopsy and amniocentesis. With the development of the 3D ultrasound transducer technology, the biopsy needle localization and tracking methods using 3D ultrasound could have more value and real-word potential. The objective of this paper is to evaluate and compare existing micro-tool localization methods in both static and dynamic situations. In the static situation, four tool-localization methods using 3D ultrasound were compared: A 3D PCA method, 3DRHT, PIP transform and the RANSAC algorithm. The localization methods were compared both with and without the ROI strategy. In the dynamic situation, a dynamic ROI update strategy was added to the static localization methods. Therefore, these methods had a relatively similar performance to the ROI-RK method.

This comparative study depends on three assumptions: (i) the intensity of the needle voxels is higher than that of background voxels; (ii) the form of the needle is a thin, long and straight cylinder; (iii) the inserting trajectory always remains along the same direction.

The organization of this article is as below: Section 2 gives the static or dynamic biopsy needle localization methods, together with the ROI-strategy for the static localization algorithms. Sections 3 and 4 introduce the simulated volumes and the simulation results respectively; the real US volumes and *ex-vivo* evaluation results are presented in Section 5; Section 6 presents the discussion and the conclusions are given in Section 7.

2. Methods

2.1. Pre-processing of 3D ultrasound volume

To enhance the contrast between the needle structure and background tissue while reducing the risk of false detection, a 3D line filter measurement initially proposed by Frangi et al. [24] and previously used by our group [21] is proposed here. The original application of the line filter was for the enhancement of vessel structures. It is a Hessian matrix based method. The Hessian matrix $\mathbf{H}(M_0)$ of the voxel M_0 is: